REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

. AGENCY USE ONLY (Leave Blank)	. REPORT DATE 12/01/05	EPORT TYPE AND DATES COVERED inal: 06/01/05-11/30/05

ITLE AND SUBTITLE **Tangible GIS for real-time human interaction with landscape models**	. FUNDING NUMBER
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. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	0. SPONSORING / MONITORING AGENCY REPORT NUMBER 48447.1-EV-11

1. SUPPLEMENTARY NOTES

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2 a. DISTRIBUTION / AVAILABILITY STATEMENT	2 b. DISTRIBUTION CODE
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3. ABSTRACT (Maximum 200 words)

New technologies that combine flexibility of digital landscape representation with 3D physical scale models are hanging users interaction with geospatial data. Coupling of open source GRASS GIS with Illuminated Clay system was nvestigated with the goal to explore the possible development of Tangible Geospatial Modeling system that allows users o interact with landscape analysis and simulations using a flexible physical model. In this system, the laser scans the nodel surface that can be modified by hand and the impact of the modification on a selected terrain parameter (slope, low) is then projected on the surface in near-real-time. Coupling with GIS provides tools needed for georeferenced data nanagement and processing, integration of data from various sources and pre-processing for the tangible environment. Example application that includes terrain modifications aimed at prevention of local flooding in a small watershed is used o demonstrate the system functionality. The investigated coupling options allow users to build scalable systems, from imple, low-cost options to sophisticated geospatial modeling environments with real-time response to landscape nodifications. Physical tangible environments have a potential to fundamentally change user interaction with digital andscape models by making them more accessible and easier to understand, improving collaboration and decision making.

4. SUBJECT TERMS Tangible GIS, landscape modeling, human-computer interaction, terrain analysis	5. NUMBER OF PAGES 8
	6. PRICE CODE

7. SECURITY CLASSIFICATION OR REPORT	8. SECURITY CLASSIFICATION ON THIS PAGE	9. SECURITY CLASSIFICATION OF ABSTRACT	0. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)

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Std. 239-18

Tangible GIS for real-time human interaction with landscape models

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Statement of the problem

New mapping technologies, such as Real Time Kinematic GPS, IFSARE or LIDAR, provide highly efficient means for 3D mapping of terrain at unprecedented spatial and temporal resolutions. In response, there is an increasing need for Geographic Information System (GIS) tools that support 3D modeling and analysis of topographic surfaces and their change. Over the past decade, powerful 3D visualization modules were developed both for GIS and for specialized applications software based on advancements in scientific visualization (Hibbard et al., 1994; Wherrett, 2000). While computer generated models of topography have been very effective for visual analysis and communication, interaction with such models and their modification can be more challenging. It becomes even more complex when the virtual terrain model is combined with results of sophisticated simulations of landscape processes that are important for prediction of impacts of terrain changes (Mitas et al. 1997). To fully take advantage of these models for problem solving and decision making, effective communication and interaction with terrain models and simulations is needed.

The complexity of geospatial analysis and modeling using GIS has been addressed by implementation of graphical user interfaces (Cartwright et al., 2001). On the one hand, GUIs with a high degree of sophistication have replaced line-driven commands of first-generation GIS. On the other hand, a number of alternative approaches for communication with GIS have been suggested, most notably those based on Virtual Environments (Germs et al., 1999). The project focused on development of a prototype, novel interface for GIS, which springs from recent work carried out in the field of Tangible User Interfaces (TUI; Underkoffler and Ishii, 1999) and is based on using a real 3D model of landscape along with the computer generated virtual model.

Objective of this short term innovative research was to bring the human-computer interaction in the area of landscape analysis, modeling and design to a new level of effectiveness by coupling the power of GIS with tangible landscape interface and demonstrate a prototype *Tangible GIS* (TanGIS) environment.

Summary of the most important results

The research focus was on the coupling of open source GRASS GIS (Neteler and Mitasova 2004) with the Illuminated Clay (IC) system (Ratti et al., 2004) with the goal to create a Geospatial Modeling environment that allows users to interact with landscape analysis using a tactile physical model of the studied landscape.

The Illuminated Clay system (Ratti et al., 2004) uses a commercially available laser scanner Minolta VIVID-900 (or its newer version VIVID 910) to capture the surface geometry of the physical clay model. The 3D scanner is coupled with a video projector that is used to project images on the landscape model. The scanner/projector pair is housed inside a casing approximately 2 m above the model. A special program based on Minolta's Software Development Kit (SDK) was developed in order to perform one scan after the other in near-real time, instead of the standard mode of operation 'scan and stop'. Results obtained as distance values from the scanner's lens are then converted into Digital Elevation Models (DEM). Terrain analysis algorithms are applied to the DEM and results are projected back on the landscape model using a video projector. The interaction loop is recursive and happens in near-real-time

providing the user with almost instant response to the changes manually introduced on the surface. Two additional projectors (or a projector and a computer display) can be coupled with the system for creating a virtual terrain model and the system interface.

The core IC software computes DEM using scanned elevation data, derives a user-selected parameter and re-projects the new map over the surface. It supports computation of parameters where only the elevation data are required as inputs - it can be therefore considered a Tangible User Interface (TUI) for terrain surface analysis. To expand the use of the system beyond the topography and include additional landscape features and processes we have explored coupling of the system with open source GRASS GIS. The tangible landscape model then can be generalized as a Tangible interface for GIS tasks that involve change in terrain surface and its attributes.

Several types of coupling of the GRASS GIS database and modules with 3D physical landscape models were investigated . The different types of coupling are based on the type of interaction between the landscape model surface representing elevation, landscape model color representing attributes and a computer system (GIS/IC):

(a) **Passive landscape model with active projection** transfers attribute map from the computer to the physical model. Model surface is static and only a color map representing attributes is projected from the computer onto the model. This one-way coupling, similar to GIS2MAP3D (Coucelo et al., 2005), involves a simple projection of a map created in the GRASS GIS graphical window over the physical model. The map can be static, such as a combination of raster and vector features (e.g., combined vegetation , roads, building footprints, and streams), or an animation representing a landscape process (water flow, spread of fire). This approach offers great flexibility for the type of data that can be displayed and additional maps can be computed using GIS modules. Implementation is simple, projecting an aligned GRASS GIS graphical window from the computer screen is adequate; for larger models and greater terrain complexity, image transformation to central projection is required.

(b) **Active landscape model with active projection** transfers elevation from the physical model to the computer and attribute map from the computer to the model. Model surface can be manually modified and the new surface elevations are transferred to the computer using 3D laser scanning. Attribute data are projected from the computer to the surface with a delay**.** To support feedback for terrain modification we have implemented this type of two-way asynchronous coupling of IC with GRASS GIS. The physical model is scanned, the elevation data are imported into GRASS GIS and interpolated into high resolution (1 mm) DEM. Selected analysis is computed for the new surface and the result is re-projected either through the option (a) or by importing the result into IC. Because the response does not happen in real time (the delay depends on the computational demands of the analysis), complex spatial modeling that involves additional map layers can be performed (e.g., erosion risk modeling that includes land
cover, soil and rainfall data along with the parameters derived from the modified, scanned model). This approach also allows us to derive vector layers from the new surface, such as new contours and stream networks, or perform analysis, modeling or optimization tasks that may include attributes stored in an external database system. Complex numerical models representing dynamic phenomena can also be supported with this option.

(c) **Active landscape model with active real-time projection** transfers elevation from the physical model to the computer and attribute map from the computer to the model in real time. Model surface can be modified while its elevation is transferred to the computer using 3D

scanning and new attribute data are projected from the computer to the surface in real-time. This two-way synchronous (real-time) coupling with GRASS GIS that provides a real-time response to manual terrain modifications requires further research and development. Several approaches are possible, such as porting selected modules relevant to terrain analysis from GRASS GIS to IC or the use of a newly developed GRASS Server with C client or a swig interface.

We have also identified additional possibilities for coupling between the digital and physical landscape representation that can be developed in the future:

(d) **Active, computer controlled landscape model with active real-time projection** transfers the elevation from the physical model to the computer, from the computer to the model, and attribute map from the computer to the model. This two-way surface coupling including the surface change will support the capabilities described by the option (c), but it will also make the surface adjustable using the digital elevation data, a capability currently supported by the pin-based system. This approach will support both manual and computer guided modification and it will "react" to the modification in real time by displaying the changes in selected terrain parameter. It will require the replacement of the clay surface by a different type of hardware.

(e) **Active, computer controlled physical model with active real-time attribute input and projection** transfers elevation from the model to the computer and from the computer to the model as well as the attribute map from the computer to the model and from the model to the computer. This approach will support all the capabilities described in (d) but it will also use the RGB scan (image) of the landscape model to capture a manually introduced change in color. This will allow us to use color coding of the surface and structures to indicate the type of land cover, permeability of structures, and other properties needed as input for landscape process modeling and decision making.

The presented set of coupling options will allow users to build scalable systems, from simple, low cost options to sophisticated geospatial modeling environments with real-time response to different types of landscape modifications. In addition, coupling with GRASS GIS provides a wide range of tools needed for georeferenced data management and processing that allow users to integrate data from various sources and pre-process them into formats suitable for the tangible environment. GRASS GIS also has a powerful 3D visualization module that further supports combination of the physical model with an interactive 3D virtual terrain model

Example application To illustrate the concept of tangible geospatial modeling environment we have used the coupled IC-GRASS GIS system to explore various structures and terrain modifications aimed at sediment control and prevention of local flooding in a small watershed. The test area was a 25 ha site at the North Carolina State University (NCSU) Sediment and Erosion Control Research and Education Facility (SECREF). Various methods for erosion and sediment control are developed and tested at this site and it has a sufficiently complex terrain to demonstrate the functionality of the tangible interface.

The 3D physical model of our test landscape at a 1:2000 horizontal scale with 6-times vertical exaggeration (Figure 1a,b) was based on a 2m resolution DEM (year 1993) interpolated from 0.6 m (2 ft) contours obtained from the Wake county GIS (Figure 1c). Airborne lidar scan of the area acquired in year 2001 is included to illustrate actual changes in topography (Figure 1d). The physical model is used as a tangible interface (Figures 2, 3) to explore the changes in topography using various structures, ditches, and basins to minimize the flooding and reduce the excessive sediment transport.

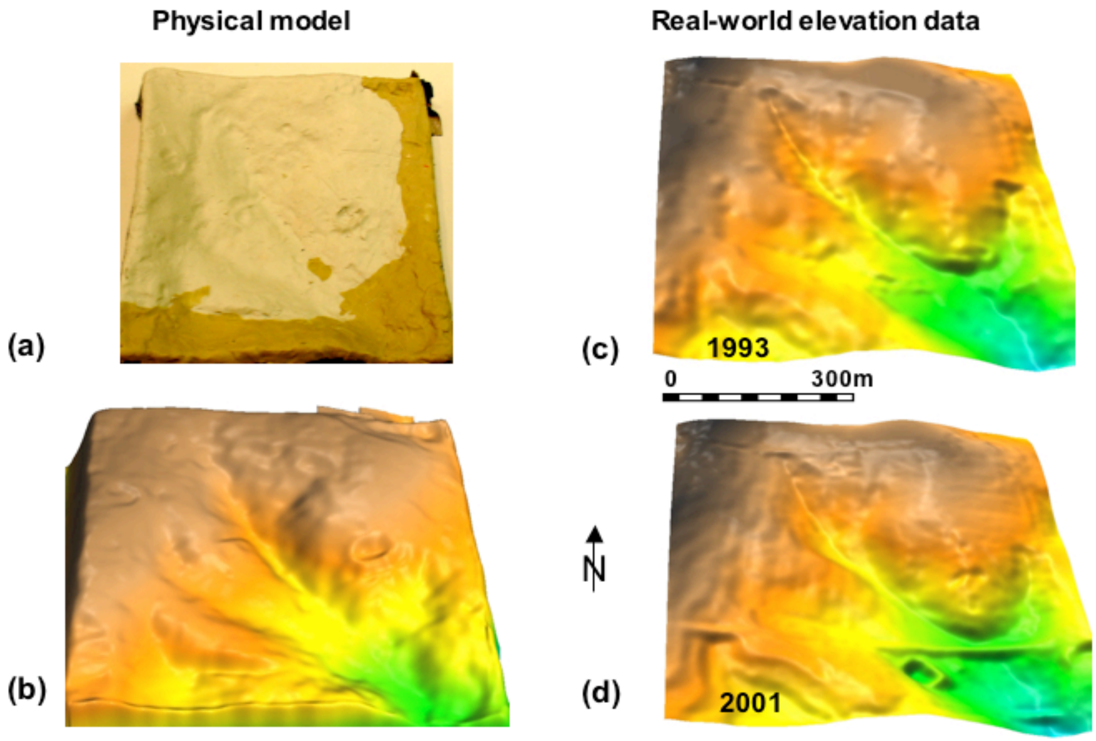

Figure 1. Elevation surface for the test site: (a) 1:2000 scale clay model; (b) 1 mm resolution DEM based on a 3D scan of a modified physical model; (c) original 2 m resolution DEM used to create the physical model; (d) 2 m resolution DEM based on 2001 year airborne lidar scan. The surfaces were visualized in GRASS GIS.

GIS-based landscape characterization layers, such as soils, land cover, footprints of structures, and roads were first projected onto the physical model surface to provide information about the properties of the modeled landscape. Surface analysis, flow routing and erosion modeling was performed in GRASS GIS for the initial terrain to assess the patterns of slope, overland water flow (Figure 2b) and sediment transport. The physical landscape model was then manually modified to explore various approaches for water flow and sediment pollution control (Figure 3).

The first set of changes involved manual modification of a convex hillslope into a shallow basin while the flow direction map was displayed and updated along with the terrain surface change. The basin shape was gradually adjusted until flow was redirected through this basin into the neighboring forested watershed, thus reducing the concentrated flow that was causing the flooding and sediment pollution. A new slope map was then projected over the modified surface to check whether the modifications did not introduce steep slopes that may cause stability problems. Slopes that exceeded the critical threshold, such as the red areas in the Figure 2b, were manually modified until the projected slope map showed stable values everywhere. The new DEM was then imported into GRASS GIS and topographic analysis and flow simulation was re-run with greater detail. The process-based hydrologic and sediment transport model allowed us to quantify the impact of the proposed change in terms of water depth and sediment flow rates for a selected design storm.

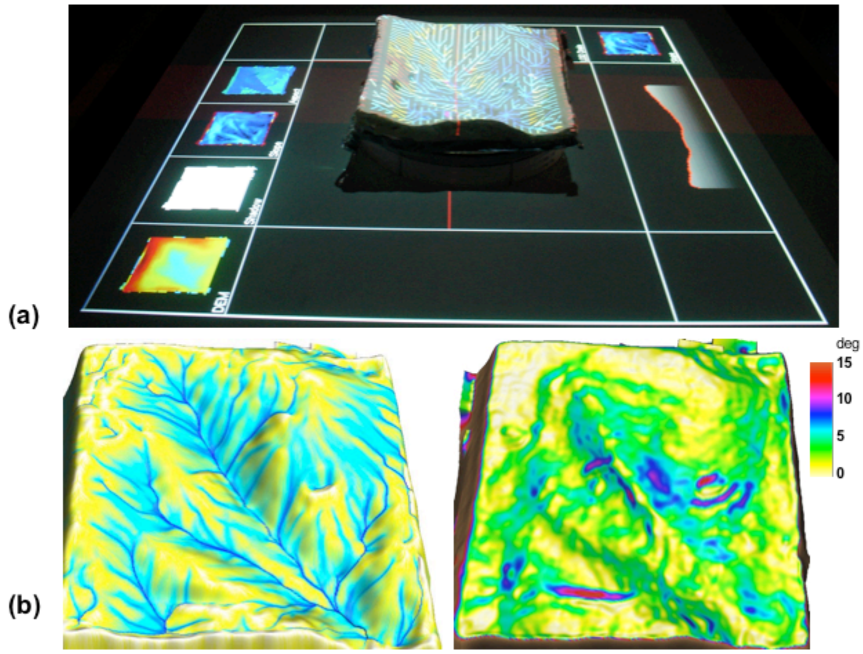

Figure 2. Clay model placed in the IC environment: (a) flow direction is projected over the surface while additional parameters (elevation, contours, slope, aspect, profile) are displayed by smaller 2D images around the worktable; (b) more detailed maps of water flow and slopes are computed for the scanned surface using asynchronous coupling with GRASS GIS.

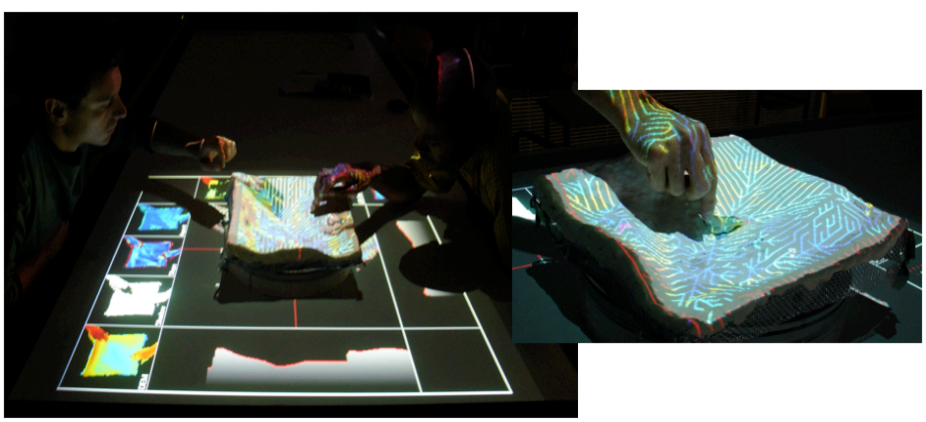

Figure 3. Physical landscape model is modified, with the impact of changes shown in real time on the clay model surface (flow pattern) and using the smaller 2D images around the worktable for elevation, slope, aspect, and selected profiles.

The second set of modifications involved addition of check-dams in the main valley. Small, dam-shaped pieces of clay were used to approximate the structures (Figure 3). Tactile environment allowed us to move a dam up and down along the valley, add second and third structure and modify their shape and size while observing the impact on water flow pattern. The flow direction map generated by IC showed interruption of flow due to check-dams, reducing the flow rate through the valley with the effectiveness dependent on the location of the structure in relation to the rates of lateral inflow. The modified DEM with the structures was then imported into GRASS GIS and a process based modeling was performed to quantify the resulting water flow depth and sediment flow rates (Figure 4). Placing larger structures in the lower section of the valley resulted in a more robust design in terms of reducing the flow rates and withstanding larger storms than a set of smaller structures located along the entire valley. Both two-way synchronous and asynchronous coupling was used for this case. In addition, this approach allowed us to investigate the dynamics of the flow and asses when the check-dams may be overtaken by storm water.

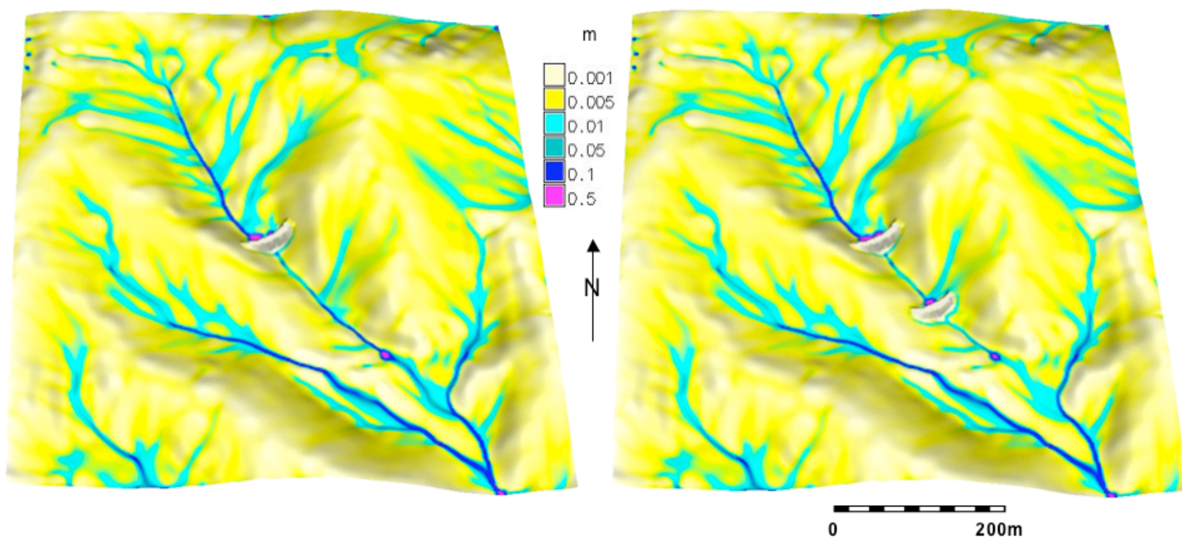

Figure 4 Water depth distribution for a single and two checkdams - output from a numerical model implemented in GRASS GIS.

Conclusion Physical tangible environments coupled with GIS and 3D visualization have a potential to fundamentally change the user interaction with digital landscape models and georeferenced data representing landscape properties and processes. For experts, the problem solving can become more efficient and the environment may increase the creativity in finding potential solutions. In the area of decision making, the system can make the digital landscapes more accessible and easier to understand when coupled with a 3D physical model, potentially leading to a more informed decision making.

Our concept that includes various levels of coupling between the physical model and GIS is flexible and "resource scalable". It can be used for very simple, low cost systems that include only a projector and a landscape model to sophisticated tangible systems that include a more expensive laser scanner and two-way real time coupling. The two-way coupling that will include the computer controlled surface and input of model surface color requires considerable

research for finding a low cost, easy to implement solution, although there are already technologies available to accomplish this type of coupling at a relatively high cost (Xenovision Mark III). In future, we can envision that large 3D physical models coupled with GIS and numerical models, capable of receiving real-time data from satellites and terrestrial sensors will be at the heart of the land use management at different communities, military installations, and can one day improve response to natural disasters and emergencies as well as help to solve day-to-day land management problems. Fort Future research program that considers creating alternative scenarios as the key initiating process (Case 2002) is an example of an Army program where the Tangible GIS environment can fulfill an important need for an environment that can bring together a diverse user community of trainers, operations personnel and natural resource managers and increase the efficiency of the sustainable installation planning.

Project management This project is a collaborative effort between the team at the Massachusetts Institute of Technology, SENSEable City Laboratory lead by Dr. Carlo Ratti and the team at the North Carolina State University Center for High Performance Simulation, lead by Dr. Mitas from the Department of Physics and Dr. Mitasova from the Department of Marine, Earth and Atmospheric Sciences. Dr. Ratti is one of the co-inventors of Illuminated Clay and the NCSU team provides the expertise in GIS and geospatial simulations. Most of the development and testing has been performed using the Internet, two visits to MIT allowed the NCSU team to work directly with the tangible user interfaces using the NCSU SECREF physical model.

Papers presented at meetings

Mitasova H., Tangible GIS: New Human-Computer Interface For Geospatial Modeling, Research briefing at USACE Topographic Engineering Center, Sept. 2005.

Manuscripts accepted

Mitasova, H., Mitas, L., Ratti, C., Ishi, H. and Harmon, R.S., Real-time Human Interaction With Landscape Models Using a Tangible Geospatial Modeling Environment, accepted to IEEE Computer Graphics and Applications, Special Issue on GeoVisualization.

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